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SOLID ROCKET AND SPACE PROPULSION STUDIES

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ABSTRACT

Studies were directed at the deflagration of heterogeneous, condensed media. Relations among ballistic properties were studied; generalized relations were derived and existing relations for testing the consistency of data from ballistic test motors were shown to be general to small error; errors in the recent literature were corrected. A new device for characterizing the ballistic properties of condensed media at high pressure with strands was devised and explored analytically. Self-pressurized constant pressure operation was shown along with capability to control the pressure level with a simple bang-bang control system. Special configurations to provide direct little difference measurements of ballistic sensitivities were presented. The Deur/Glick serial sandwich model for heterogeneous propellant combustion was modified to overcome the "continuation" *problem implicit in that model. Results showed ignition delays of correct magnitude and, with physical reasoning, demonstrated that* **the ZN methodology cannot be applied to heterogeneous propellants in its present form.** [illegible] Rocket [illegible]
Solid [illegible] Rocket [illegible]

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1.0 INTRODUCTION

Combustion/flowfield interactions are crucial to the performance of chemical propulsers. In solid rocket motors they appear primarily as condensed phase media deflagration/flowfield interactions. They modify mass burning rate, impact performance, and dominate combustor stability. Qualitative mechanistic understanding of the governing phenomena has not been achieved to date because of inadequate understanding of the self-induced flowfield and the deflagration phenomena of condensed, heterogeneous propellant. The *self-induced* flow field is unique in fluid mechanics because deflagration of heterogeneous, condensed media is spatially and temporally nonsteady; the latter leads to the existence of finite turbulent kinetic energy at the flow boundary. Stationary state calculations by Beddini[1] show that this "boundary turbulence" modifies the turbulence field and strongly impacts profile transition in semi-enclosed porous ducts. These modifications of the turbulence field are of particular importance because it is generally conceded that turbulence modification of transport phenomena is the principal mechanism for flowfield/deflagration interactions[1,2] Thus, the qualitative nature of the interaction is clear: deflagration of heterogeneous condensed propellants begets the flowfield and supplies boundary turbulence; the flowfield with its dynamics amplifies and redistributes the input turbulent kinetic energy; and the turbulence field modifies the deflagration process thereby completing the loop.

It is clear that both the heterogeneity of the condensed phase and deflagration phenomena at the scale of the heterogeneities are important to deflagration/flowfield interactions. Considerable effort has been made to describe this phenomena theoretically. Reasonable success has been achieved for the stationary state although formulational regions where the models fail miserably exist. Unfortunately, little success has been achieved with the nonstationary problem. Two common flaws pervade both situations: neglect of thermal transients in the condensed phase at the scale of the heterogeneities (observed in micro-thermocouple experiments) and deviations (and nonstationarity) of heterogeneity populations on the deflagrating surface from the planar statistics assumed. The former is important because heterogeneous propellant deflagration is intrinsically nonsteady and at the scale of the heterogeneities condensed phase temperature gradients profoundly effect nonsteady deflagration processes. The latter is important because it means that what we think is on the burning surface (planar statistics) probably isn't! Since the surface is rough, one suspects that the greatest disparities occur at the smallest scale of the heterogeneities. The population statistics problem also impacts the response of the deflagration rate to environmental fluctuations.

It has been assumed in some studies that the condensed phase possesses long range order so that deflagration through the ordered media leads to an intrinsically nonsteady process (layer frequencies) at the spatial scale of that ordering. These effects have been explored theoretically[3-5]. However, since heterogeneous propellants are prepared by mixing and significant anisotropy has not been observed in either physical or ballistic properties, long range order in the condensed phase is improbable. Therefore, the ordered condensed phase models are not particularly realistic. To overcome this problem Deur and Glick[6] created a serially layered model with finite differences in layer properties and randomly ordered layers. Calculations with the model showed that environmental fluctuations did not correlate with the randomly ordered structure of the condensed phase to first order. Therefore, the heterogeneity response postulated by Cohen and Strand[5] appears to be physically implausible. However, the Deur/Glick model exhibited a fatal flaw; combustion terminated spontaneously with transitions from fine to coarse pseudo-propellant layers whenever rate changes were significant. Therefore, with *interesting* propellants a "continuation problem" exists.

In addition to serially layered models several versions of parallel layered models have been developed[7]. These models arise naturally when one spatially averages over the deflagrating surface. Typically, these models give the mean nonsteady response in terms of the responses of the individual pseudo-propellants that comprise the parallel layers. A variety of techniques have been employed to deduce the nonsteady behavior of the individual layers. The most general of the techniques employed is the ZN methodology[8]. In this approach steady state deflagration information is employed to characterize heat feedback from the gas phase to the nonreactive condensed phase. Therefore, rate sensitivities to pressure and initial propellant temperature are extremely important to these formulations. These can be computed from stationary state models[9]; they can also be extracted from experimental data if the data base is sufficiently large[10].

As noted above, application of ZN methodology requires accurate knowledge of the rate sensitivities $n=[\partial \ln r/\partial \ln p]_T$ and $\sigma_p=[\partial \ln r/\partial T]_p$. Data for these sensitivities come from burning rate data obtained from strands and/or ballistic test motors. It is important to note that accurate burning rate data are necessary because differentiation (an error enhancing process) is required. Recent studies by Cohen and Flanigan[11] have shown that these sensitivities generally depend upon both pressure and initial propellant temperature [$n=n(p,T), \sigma_p=\sigma_p(p,T)$]. Consequently, as previous relations among ballistic properties had been derived under a constant sensitivities assumption, new differential relations that accommodated variable sensitivities were derived. Moreover, since burning rate data are only available at discrete pressures and temperatures, all sensitivities are of necessity the result of finite difference operations. Therefore, Cohen and Flanigan accounted for finite difference effects and found that significant discrepancies occurred between finite difference and differential results. However, the finite difference result derived for π_K contains a differential quantity in the denominator. This suggests that errors may exist in their derivations.

The objectives of this work were to explore the deflagration of heterogeneous propellants and the self induced flowfield in semi-enclosed porous ducts in order to increase understanding of the governing phenomena.

2.0 ACCOMPLISHMENTS

2.1 Relations Among Ballistic Properties

A major difficulty with Reference 11 is that confusion has arisen relative to differential and mean values. Cohen and Flanigan take considerable effort to illustrate the difference between these situations for the simple case where $dn=dK=dC^*=d\rho=dT_f=0$. However, in this simple case the difference found appears to be due solely to differences in the way σ_p is defined [in one case $\sigma_p=\Delta\ln r/\Delta T$ while in the other $\sigma_p=\Delta r/r\Delta T$]. Consider this situation. From quasi-steady continuity

$$r_1\rho A_b=A_t p_1 g_c/C^* \qquad [1]$$

and

$$r_2\rho A_b=A_t p_2 g_c/C^* \qquad [2]$$

Therefore, for a constant area ratio process one obtains

$$r_1/r_2=p_1/p_2 \qquad [3]$$

Employing the definitions of π_K and σ_p mean values of these sensitivities can be computed by *integrating over the dK=0 path viz*

$$\bar{\pi}_K=\int_1^2 \pi_K dT/\Delta T=\ln(p_2/p_1)/\Delta T \qquad [4]$$

$$\bar{\sigma}_p=\int_1^2 \sigma_p dT/\Delta T \qquad [5]$$

For a dK=0 path employ the identity $\sigma_p=\sigma_K-n\pi_K$ and obtain

$$\bar{\sigma}_p=[\ln(r_2/r_1)-n\ln(p_2/p_1)]/\Delta T \qquad [6]$$

With [3,4,6]

$$\frac{\bar{\pi}_K}{\bar{\sigma}_p}=\frac{1}{1-n} \qquad [7]$$

Since this is precisely the result obtained for a differential change under these assumptions, difference and differential expressions are identical for this restricted situation **in direct contradiction to Reference 11!**

For the relation among ballistic properties in ballistic test motors it can be shown in general that

$$\pi_K=\frac{\sigma_p+\pi_C+[\partial\ln(\rho_p-\rho_g)/dT]_K}{1-n} \qquad [8]$$

To obtain the Cohen/Flanigan expression expand n in a Taylor series about the reference state $()^{\circ}$, truncate that expression at first order, and employ the identity

$$[\partial n/\partial T]_K=[\partial n/\partial T]_p-\pi_K[\partial n/\partial \ln p]_T \qquad [9]$$

to obtain

$$\pi_K=\frac{\sigma_p+\pi_C+[\partial\ln(\rho_c-\rho_g)/\partial T]_K}{1-n^{\circ}-[(\partial n/\partial T)_p+\pi_K(\partial n/\partial \ln p)_T]^{\circ}[T-T^{\circ}]} \qquad [10]$$

If the finite temperature difference is replaced by a differential temperature difference, the Cohen/Flanigan result is recovered. However, this is still a **differential** expression. That is, **the π_K computed with [10] is not a mean value for the T° to T range.**

To obtain an appropriate mean value for π_K the differential expression from [8] must be integrated over the path of the process. Consequently,

$$d\ln p=\frac{\sigma_p+\pi_C+[\partial\ln(\rho_c-\rho_g)]_K}{1-n}dT \qquad [11]$$

If n, C*, etc are known functions of p,T this differential expression can be integrated over the range from state 1 to state 2 and the mean value of π_K

determined from the definition. This methodology allows for variable sensitivities in a natural way.

In a recent work Gaunce and Osborn[12] derived another expression for π_K=func(σ_p,etc) that included sensitivities of sensitivities. This expression was reported to be the only completely general expression in existence. However, it was found to be an algebraic identity of the expression derived previously by Reference 13. From St. Robert's law lnr=lnc+nlnp so that differentiation gives

$$\sigma_K=[\partial \ln c/\partial T]_K+n[\partial \ln p/\partial T]_K+\ln p[\partial n/\partial T]_K \qquad [12]$$

With the general relation $\sigma_K=\sigma_p+n\pi_K$ [12] becomes

$$[\partial \ln c/\partial T]_K=\sigma_p-\ln p[\partial n/\partial T]_K \qquad [13]$$

Substituting this result into the expression of Gaunce and Osborn yields [8]. Therefore, the results are mathematically identical! Unfortunately, they are not identical at a practical level because sensitivities of sensitivities introduce additional error when operating with real ballistic data that is of necessity imperfect. This is easily demonstrated by computing π_K from data supplied by Gaunce and Osborn [note that the absence of error in Table 5 for the Gaunce and Osborn expression results from the arbitrary definition of null error for that result!] which gives different numerical results for mathematical identities. Consequently, Gaunce and Osborn's expression for π_K is overly complex.

The necessity for accurate and consistent ballistic data for sensitivity calculations suggests that the procedure developed and employed by Geckler and Sprenger be used to improve the quality of the data base by eliminating inconsistent data. It has been shown in Reference 13 that this methodology, derived for constant sensitivities, is general and applies to variable sensitivities. For details see Reference 13.

2.2 Ballistic Test Devices

As noted previously burning rates are determined experimentally in either strand burners or ballistic test motors. Strand burners connected to large surge tanks yield data at essentially constant pressure. However, operation of this type device at high pressures is difficult if not impossible because of purge difficulties. Therefore, strand data are collected at high pressure in closed burners that of necessity do not maintain constant pressure. This is not a problem with ballistic test motors because they are self pressurizing as long as nozzle plugging is not a problem. However, in all cases only absolute rate data are obtained so that differences required to obtain the sensitivities introduce appreciable error. A new test device - a hydraulic strand burner - has been devised that permits self pressurized strand burning at elevated pressures. Moreover, a manifolding arrangement has been devised that permits direct measurement of the little difference in burning rate at different states appropriate for either n or σ_p measurement. The concepts are well described in Reference 14

2.3 Combustion Modeling

The serially layered model of Deur and Glick was modified to overcome the "continuation" problem noted above. The modifications were limited to bimodal propellants although the methodology could be applied to the polymodal situation. In a bimodal formulation of coarse and fine particulates the size dispartity leads to a significant probability that both coarse and fine particulates will be adjacent to fines. As ignition delay increases with particle size, the fine pseudo-propellant will, to a reasonable approximation, behave like a homogeneous propellant. Therefore, the coarse pseudo-propellant is literally surrounded by an ocean of fine pseudo-propellant that behaves like homogeneous propellant. Previous calculations[6] indicated that spontaneous extinguishment occurs only in transitions from fine to coarse pseudo-propellant. Therefore, when the coarse pseudo-propellant extinguishes, the fine pseudo-propellant continues burning. Consequently, the extinguished coarse particle sees a surrounding flow from the fine pseudo-propellant and heat transfer from that flow will add energy to the unignited particle. The flow situation will be similar to separated flow at the trailing edge of a sphere.

This physical situation was modeled and embedded in the basic Deur/Glick model. Calculations showed that oxidizer particle ignition delays computed in this manner were of proper magnitude[15]. Unfortunately, there was insufficient computer time for the random process to achieve stable means for the pressure coupled response function. However, a reasonable estimate was obtained by smoothing the computed results. This showed that multiple maxima type response was not achieved. This is not a complete surprise if one considers the physics of the process. In this simple model the fine pseudo-propellant behaves like a homogeneous propellant - *it is always burning!* However, the coarse pseudo-propellant exists in two states; unignited and ignited. In the unignited state it is dormant and does not contribute to the pressure coupled response. However, the ignited state is not an equilibrium state because of the augmented energy store in the condensed phase accumulated during the ignition delay. This excess of sub-surface energy will force the ignited state burning rate to higher than equilibrium values. ***Consequently, the coarse pseudo-propellant will behave as an inert diluent during its ignition delay period and somewhat like fine pseudo-propellant during its ignited state.*** Note that the balance between these processes will depend upon particle size, pressure, initial temperature, and the deflagration characteristics of the fine pseudo-propellant.

The realization that heterogeneous propellant deflagration is nonsteady at the single particle level has considerable importance. For example, it implies that the ZN methodology in its present incarnation is not applicable to heterogeneous propellants. To see this note that the sensitivities employed with the ZN method are those of the *mean* state. That is, the sensitivities one obtains from experimental data are of necessity those for a mean of ignited and unignited states. However, only the ignited states have reality for nonsteady response! Therefore, the present ZN methodology is not applicable to parallel layer models.

2.4 Miscellaneous

Rocket motors were designed for concurrent mean and nonsteady pressure and nonsteady velocity measurement. These designs were implimented. Unfortunately, reduced data were not achieved because of a data acquisition system failure; power conditioning at the TSPC is marginal at best; power "glitches" are not conducive to microcomputer operation.

3.0 CONCLUSIONS

The works performed in this study have shown that the finite difference $\pi_K = \pi_K(\sigma_p, \text{etc})$ relation derived by Reference 11 is in actuality a differential relation; a methodology for obtaining the correct relationship was derived. Relations among ballistic properties were derived and it was shown that the consistency procedure devised by Geckler and Sprenger for constant sensitivities applies to the variable sensitivity situation. A new experimental device for self-pressurized deflagration at either constant or controllable pressure was devised and explored analytically. This device has capabilities for measuring performance related parameters and, in special configurations, is capable of direct measurements of burning rate differences. The serially layered model of Deur and Glick was modified to overcome its "continuation" problem. Results and physical reasoning indicate that the present ZN methodology is not applicable to heterogeneous propellants.

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